Measurement of the W Boson Mass and Width at the D0 experiment

D. Boline
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

I present a precise measurement of W boson mass measurement in electron decay channel using data collected by the D0 detector at the Fermilab Tevatron Collider. A binned likelihood fit method is used to extract the mass information from the transverse mass, the electron transverse momentum and missing transverse energy distributions. I also present a precise direct measurement of W boson width using the events with large transverse mass. The W mass result can be used to put stringent indirect limits on the Standard Model Higgs boson mass.

1. Introduction

In 2009 the DØ experiment published precision measurements of both the W boson mass [1] and width [2]. Both measurements make exclusive use of the decay channel $W \to e\nu$, due to the excellent energy precision of the DØ Calorimeter. The uncertainty on our knowledge of M_W is currently one of the strongest factor limiting our ability to constrain the mass of the standard model Higgs Boson. The measurement of Γ_W is important as a precision test of the Standard Model (SM), as within the SM the W boson width is related to the W boson mass through the expression given in Eq. 1.

$$\Gamma(W \to l\nu) = \frac{G_F}{\sqrt{2}} \frac{M_W^3}{6\pi} (1 + \delta_{SM})$$

(1)

Where $f_{QCD} = 3(1 + \alpha_S(M_W^2)/\pi)$ to first order in α_S and $\delta_{SM} \approx 0.021 \pm 0.005$.

1.1. Tevatron Collider

We obtain our W bosons from the Tevatron Collider at Fermi National Accelerator Laboratory (Fermilab). The Tevatron collides protons and antiprotons at a beam energy of 980 GeV for a center-of-mass energy or 1.96 TeV. Both of these measurements make use of 1 fb^{-1} of data collected up to 2006, the Accelerator Division at Fermilab has done an excellent job of maximizing delivered luminosity to the DØ experiment, and as of September 30th we have ≈ 10 fb^{-1} of data available.

1.2. DØ Detector

Both of these measurements make extensive use of two components of the DØ Detector [3], the Calorimeter to measure the electron energy and the hadronic recoil, and the Tracking Detector to identify electron tracks. DØ uses a liquid Argon Calorimeter (Fig. 1), with a Central Calorimeter (CC) extending to $|\eta| < 1.1$, North and South End Cap (EC) Calorimeters from $1.5 < |\eta| \lesssim 4$, in addition there is a Scintillating Inter Cryostat Detector (ICD) between the CC and EC with $1.1 < |\eta| < 1.5$. Both measurements principally use the CC calorimeter. The CC is broken up longitudinally into an Electro-Magnetic (EM) portion and both a fine and course Hadronic (fHad,cHad) portion. The EM portion is closer to the beam, and has a high precision for measuring electron energies. The fHad portion contributes to the measurement of the recoil of the W boson, while the cHad is not used due to its larger noise.

The Tracking Detector (Fig. 2) is composed of two parts. The Silicon Microstrip Tracker (SMT) sits closest to the beam, and provides a precise measurement of the z and ϕ of a given track, allowing for accurate vertexing. The Central Fiber Tracker (CFT) is less precise in z, but offers high precision in ϕ and gives a precise measurement of the p_T of high p_T tracks. Both tracking detectors sit within a Solenoid magnet with a 2 T field.

2. Event Selection

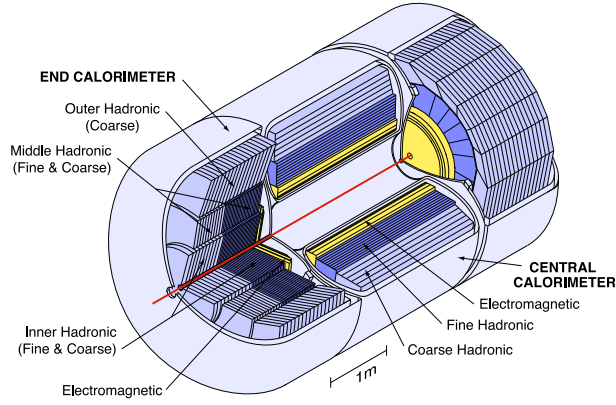To select the W boson sample, we require a single electron with:
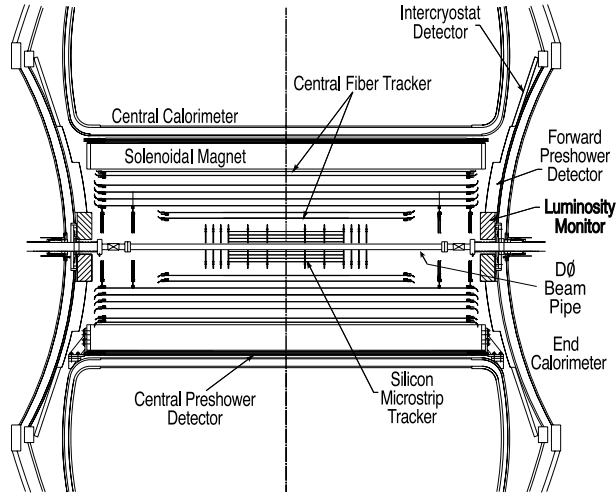
- $p_T^e > 25$ GeV

Figure 1: DØ Calorimeter.

Figure 2: DØ Tracking Detector.

- $|\eta_e| < 1.05$

- Spatially matched track with hits in the SMT

We also require:

- $\not{E}_T > 25$ GeV

- $u_T < 15$ GeV, where u_T is the recoil off the boson.

- $50 < m_T < 200$ GeV where $m_T = \sqrt{2p_T^e \not{E}_T (1 - \cos\theta)}$.

We obtain a sample of 499830 candidate events.

In addition to the W boson sample used for the mass measurement we select a calibration sample composed of Z bosons. For the Z boson calibration sample, we require two electrons with the same selection criteria as the W boson sample, $u_T < 15$ GeV, and in addition we require $70 < m_{ee} < 110$ GeV. We obtain a sample of 18725 candidate Z events.

3. Backgrounds

The three major backgrounds to this analysis come from $Z \rightarrow ee$, QCD multijet events, and $W \rightarrow \tau\nu_\tau \rightarrow e\nu_e\nu_\tau\nu_\tau$. The $Z \rightarrow ee$ background arises from events where one electron passes the $W \rightarrow e\nu$ selection while the second electron falls into the the ICD region which this analysis doesn't use when calculating $\not{E}_T$. We estimate

the size of the $Z \to ee$ background using events which pass the $W \to e\nu$ selection but also contain a track pointing towards the ICD region. This background is estimated to make up $0.91 \pm 0.01\%$ of the total $W \to e\nu$ sample.

The QCD multijet background arises when a jet fakes the signature of an electron. We estimate the size of the background using a sample without the requirement of a track match to the electron. The size of this background is estimated to be $1.49 \pm 0.03\%$ of the sample.

The $W \to \tau\nu$ background is irreducible, as it has both a high p_T electron and large $\not{E}_T$. We estimate the size of this background using a sample of simulated events obtained using the PYTHIA [4] Monte Carlo event generator. These events are estimated to comprise $1.60 \pm 0.02\%$ or the sample.

4. Monte Carlo Simulation

A crucial part of both measurements is a precise theoretical model of both W and Z boson production. To obtain this high level of precision we use the RESBOS event generator. RESBOS combines a next-to-leading-order (NLO) calculation at high boson p_T with a next-to-leading-log (NLL) resummation at low boson p_T, reproducing the observed p_T spectrum in $Z \to ee$ events. To simulate the effect of photon emission from final state electrons we use the PHOTOS subroutine.

Finally we use a detailed fast parametric Monte Carlo simulation (fastMC) to model the interaction of the particles produced in W and Z production with our detector. This fastMC contains tuned models of both the electron shower and the hadronic recoil.

5. Electron Energy Response

The most important component of our model of the electron shower is the energy response of the EM calorimeter. The mass and width of the Z boson were measured to a very high precision at the LEP Collider, and we use the values obtained there to calibrate our own detector. This means that we are effectively measuring M_W/M_Z and Γ_W/M_Z. We model non-linearities in the energy response of our calorimeter through detailed GEANT [5] simulations, then perform a fit to the remaining linear energy response. The measured energy is related to the true energy by: $E^{measured} = \alpha E^{true} + \beta$, where α is the energy scale and β is the offset. This relationship is put into our detailed fastMC, templates are formed with various values of α and β, and negative-log-likelihood fit is performed to find the values of α and β most consistent with the observed Z sample (Fig. 3).
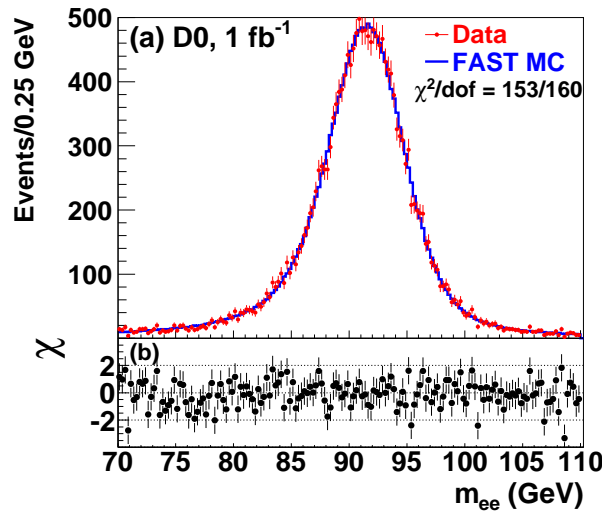

Figure 3: Comparison between Z peak in data and in fastMC after fitting electron energy scale and offset.

6. Hadronic Recoil Model

We use a parametrized model to simulate the interaction of the hadronic recoil with our detector. This parametrized model contains two parts, a hard component related to the p_T of the boson, and a soft component coming from detector noise and underlying event. The hard component is modeled using a special sample of $Z \rightarrow \nu\nu$ Monte Carlo events run through DØ's detailed GEANT simulation. The soft component is broken into a zero bias (ZB) component, where there is no requirement for an interaction vertex in the event, and a minimum bias (MB) component, where exactly one interaction vertex is required. Both the ZB and MB samples are obtained directly from data. The final parametrized model is then tuned using the $Z \rightarrow ee$ data sample.

A second model of the hadronic recoil has also been obtained, using a library of recoil events from the $Z \rightarrow ee$ sample. This model is used as a cross check and is found to be in good agreement with results obtained with the parameterized model.

7. Mass Measurement

The measurement of the mass is performed using a binned likelihood fit comparing fastMC templates at set M_W's to the data. We repeat the measurement using the distribution of three observables: the transverse mass m_T (Fig. 4), the transverse momentum of the electron p_T^e (Fig. 5), and the missing transverse energy $\not{E}_T$ (Fig. 6). In each case the fit range has been adjusted to minimize the total uncertainty.
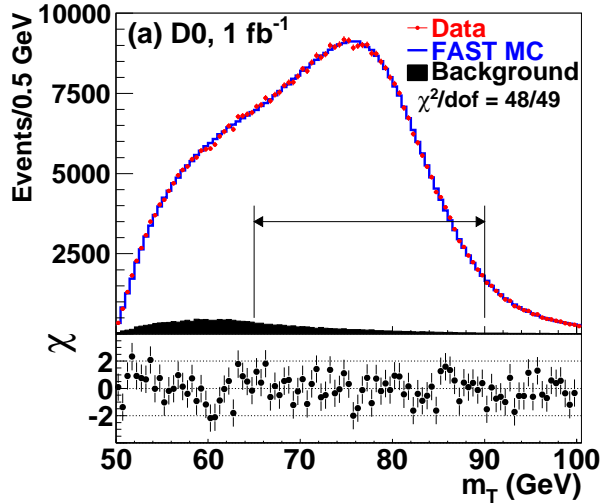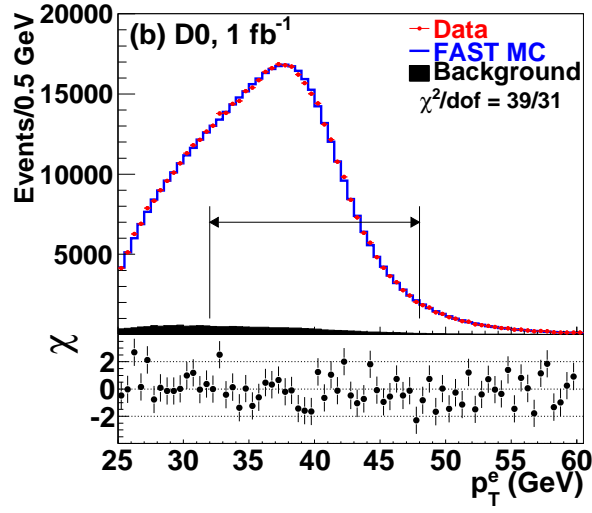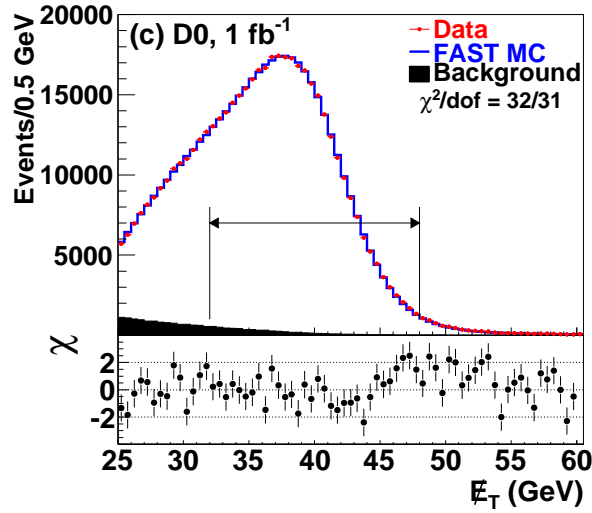

Figure 4: M_T distribution.

8. Systematic Uncertainties of the Mass Measurement

The largest systematic uncertainty by far is the uncertainty on the electron energy calibration, and this is limited by the statistics of the Z sample. The largest theoretical uncertainty comes from the parton distribution functions (PDF's), it should be remarked that this uncertainty was obtained using the PYTHIA event generator, which doesn't accurately reproduce the boson p_T spectrum. The full list of uncertainties is given in Table I

9. Width Measurement

The W width measurement uses the m_T distribution in the range $100 < m_T < 200$ GeV (Fig. 7). As in the mass measurement templates are formed with varying values of Γ_W and a fit is made to the data distribution.

Figure 5: p_T distribution.

Figure 6: $\not{E}_T$ distribution.

10. Systematic Uncertainties of the Width Measurement

The systematic uncertainty for the width measurement is dominated by the recoil model (Table II).
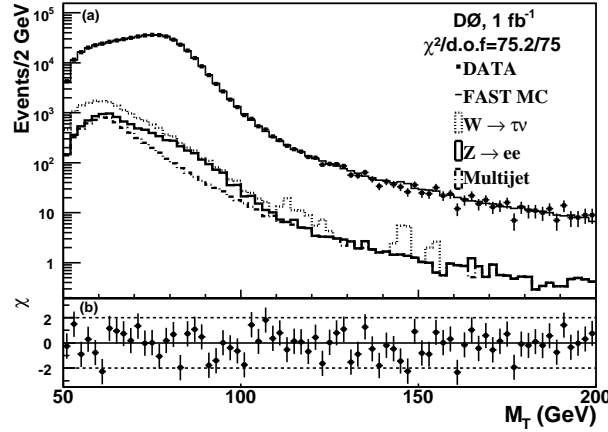
11. Results

The results of our measurements are given in Eq. 2 and 3. Comparisons to the CDF and LEP measurements, along with the combination are given in Fig.'s 8 and 9, for the combination the measured width is adjusted to use the measured mass and the measured mass is adjusted to use the measured width [6] [7], thus the inconsistency between Eq.'s 2 - 3 and Fig.'s 8 - 9 .

$$
\begin{aligned}
m_W &= 80.401 \pm 0.021 \text{ (stat) } \pm 0.038 \text{ (syst) GeV} \\
&= 80.401 \pm 0.043 \text{ GeV}
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
\Gamma_W &= 2.028 \pm 0.039 \text{ (stat) } \pm 0.061 \text{ (syst) GeV} \\
&= 2.028 \pm 0.072 \text{ GeV}
\end{aligned}
\tag{3}
$$

Table I: Systematic Uncertainties of M_W measurements.

Source	ΔM_W (MeV)		
	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

Figure 7: M_T distribution used in determination of W boson width.

12. Conclusion

The DØ m_W measurement is currently the most precise single experiment result. We have to date collected an order-of-magnitude more data than the results presented. We expect a substantial improvement in our precision. With 10 fb^{-1} we anticipate a electron energy scale uncertainty of ≈ 15 MeV and a total systematic uncertainty of ≈ 25 Mev.

References

1 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 141801 (2009) [arXiv:0908.0766 [hep-ex]].

2 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 231802 (2009) [arXiv:0909.4814 [hep-ex]].

3 V. M. Abazov *et al.* [D0 Collaboration], Nucl. Instrum. Meth. **A565**, 463-537 (2006). [physics/0507191 [physics.ins-det]].

4 T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna, E. Norrbin, Comput. Phys. Commun. **135**, 238-259 (2001). [hep-ph/0010017].

5 R. Brun, R. Hagelberg, M. Hansroul, J. C. Lassalle,

Table II: Systematic uncertainties on the measurement of Γ_W.

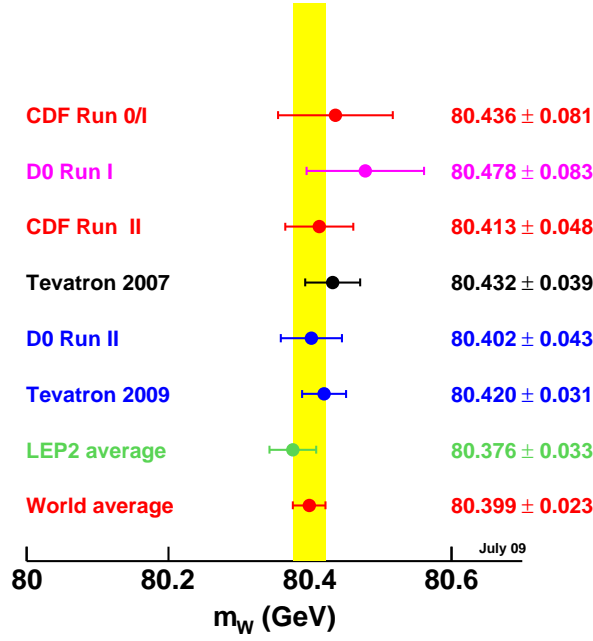| Source	$\Delta\Gamma_W$ (MeV)
Electron energy scale	33
Electron resolution model	10
Recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

Figure 8: m_W measurement at DØ compared with other experiments and SM theory.

6 [Tevatron Electroweak Working Group and CDF and D0 Collaboration], arXiv:0908.1374 [hep-ex].

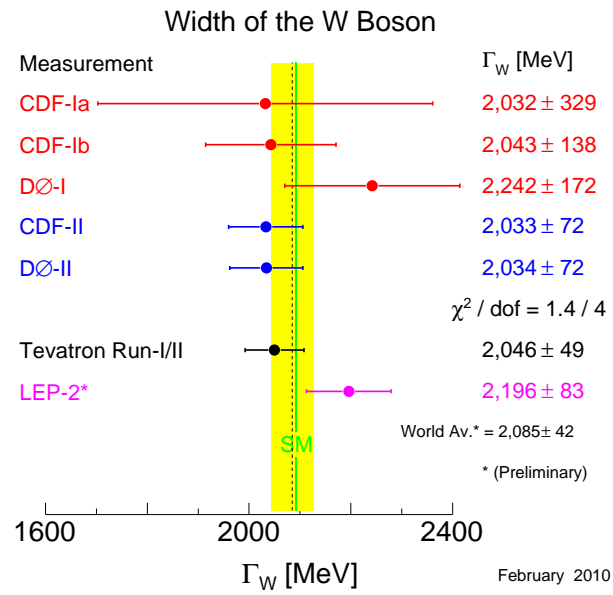7 [Tevatron Electroweak Working Group Collaboration], [arXiv:1003.2826 [hep-ex]].

Figure 9: Γ_W measurement at DØ compared with other experiments and SM theory.